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Absorption Measurement of Hydrogen Molecules in the Early Universe

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Abstract

We investigate the observability of hydrogen molecules in absorption. The absorption efficiency of the hydrogen molecules become comparable with or larger than that of the dust grains in the metal-poor condition expected in the early Universe. If we can use bright infrared continuum sources behind the molecular gas clouds, the absorption measurement of the hydrogen molecules will be an important technique to explore the primordial gas clouds that are contracting into first-generation objects.

Key words: Infrared: ISM: lines and bands — Galaxies: formation — ISM: clouds, molecules

1. Introduction

Molecular hydrogen is the predominant constituent of the dense gas in the Universe. One of the most important questions in current astrophysics is how the first generation objects formed from the primordial gas that was not polluted by heavy elements (e.g. Omukai & Nishi 1998). Theoretical models should be confirmed by observations to establish a more realistic scenario of the first generation objects in the Universe.

While in the local Universe, molecules containing heavy elements (e.g. CO, H_2O) are good tracers of the amount of molecular hydrogen, they are expected to be significantly depleted in the early Universe, though some CO emission lines have been detected for high-z objects (e.g. Ohta et al. 1996). We need a technique for measuring molecular hydrogen directly. Petitjean et al. (2000) have reported a direct measurement of H_2 molecules in the ultraviolet. Table 1 describes some important transitions of hydrogen molecules. The transition probabilities of ionization and dissociation lines are so large that they are useful for detecting thin layers and small amounts of the molecular gas, but useless for detecting dense gas clouds. On the other hand, molecular hydrogen has well-known vibrational and rotational transitions in the infrared (IR) region. Their transition probabilities are very small because hydrogen molecule, a diatomic molecule of two identical nuclei, has no allowed dipole transitions but has allowed quadrupole transitions.

These transitions of the hydrogen molecule can have both emission and absorption. Vib-rotational and rotational line emission from hydrogen molecules are useful tools to analyze dense ($> 10\,\mathrm{cm}^{-3}$) and hot (> 300 K) gas. Expected emission line intensities of molecular hydrogen were calculated by Ciardi & Ferrara (2001). According to their result, direct measurement of the emission lines of molecular hydrogen is very difficult due to their weakness. On the other hand, if there is a strong IR continuum source behind or in the molecular gas cloud, absorption measurements of these transition lines may be possible. The absorption measurement has the great advantage that the column density of the absorber can be derived with fewer assumptions.

However, we should note that the absorption by dust in the cloud is usually larger than the absorption by H_2 molecules. If the absorber is metal rich as in the ISM of the Galaxy, the extinction by dust causes the emergent continuum flux to decrease fast, thus making it difficult to observe small absorption signals (Lacy et al. 1994). Fortunately, metal abundance is expected to be significantly lower in earlier epochs of the Universe; hence the dust absorption is considerably less than that in the Galaxy. Therefore, hydrogen molecular lines can be detected in absorption against bright IR sources more easily in the early Universe than in the Galaxy. Such observation will be feasible with the advent of proposed space missions for large IR telescope facilities, e.g. *SPICA* (*HII/L2*; Nakagawa et al. 2000), *SPIRIT* (Mather 2000).

In this paper we investigate this possibility and consider what we can learn from such observations. The rest of the manuscript is as follows: In Section 2 we present the formulation of the intensity of absorption by hydrogen molecules. Our results are shown in Section 3. We discuss some relevant issues in Section 4.

2. Calculation

Assuming a uniform, cool gas cloud ($kT_{\rm ex} \ll h\nu$), the optical thickness of the line absorption, $\tau_{\rm line}$ is

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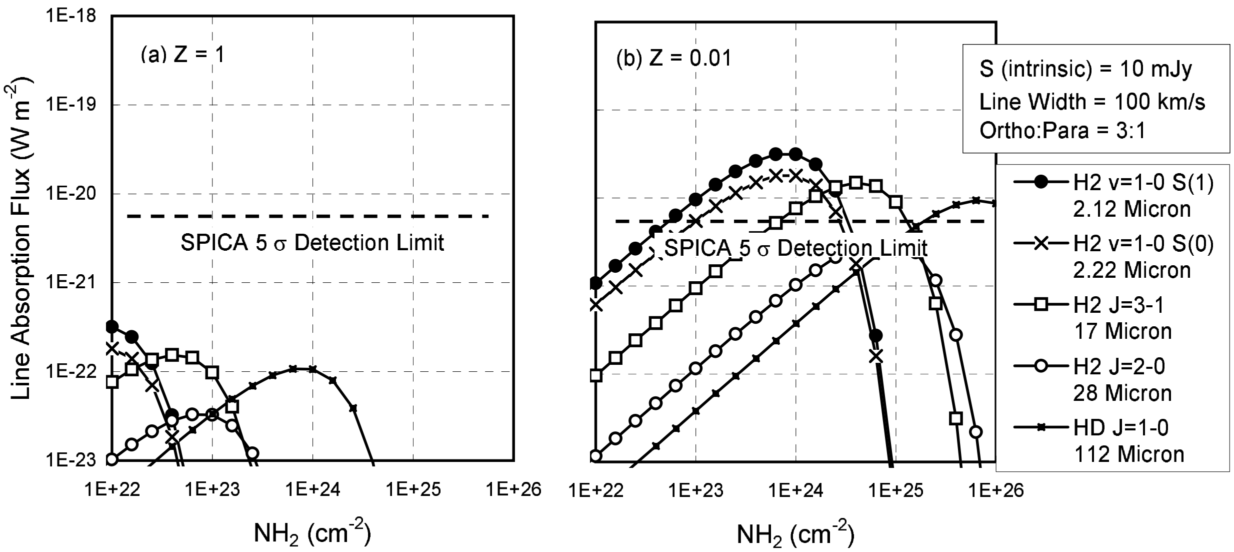

Fig. 1. (*a*) Absorption line flux expected for a cloud with the Milky Way heavy element abundance ($Z = 1$) in front of a 10 mJy source. (*b*) Same as (*a*) but the heavy element abundance is $Z = 0.01$.

Table 1. Transitions of molecular hydrogen.

Transition	Wavelength	A coefficients
ionization and dissociation	UV	large
vib-rotational transitions	NIR (2 μm)	small
rotational transitions	MIR (28, 17, $\cdots$ μm)	small
rotational transitions of HD	FIR (112, 56, $\cdots$ μm)	intermediate

$$\tau_{\rm line} \simeq \frac{\lambda^3}{8\pi}\left(\frac{g_{\rm u}}{g_{\rm l}}\right) A_{\rm ul} N \frac{1}{\Delta v} \,, \qquad (1)$$

where the subscripts u and l indicate the upper and lower levels of a transition, $g_{\rm u}$ and $g_{\rm l}$ are the degeneracy of each state respectively, $A_{\rm ul}$ is the Einstein's A coefficient, N is the column density of the molecules in the lower state, and Δv is the line width in units of velocity. Here we assume that almost all the molecules occupy the lowest energy state. As is well known, in the optically thin case, the column density can directly be derived from the equivalent width, which is nearly equal to the product of $\tau_{\rm line}$ and Δv.

The absorption line flux in the extinction free case, $I^{\rm abs}_{\rm line,0}$, is obtained by

$$I^{\rm abs}_{\rm line,0} = S\Delta\nu\,(1 - \exp(-\tau_{\rm line}))\,, \qquad (2)$$

where $\Delta\nu$ is the line width in units of frequency and S is the continuum flux of the IR source behind the cloud. The line width and the source flux are assumed to be $100\,{\rm km\,s^{-1}}$ and 10 mJy, respectively. We can scale the results of this calculation for other source fluxes, for example, based on the capability of the experimental set up. Assumed parameters are listed in Table 2.

Next, we consider about the dust extinction which is denoted by

$$\tau_{\rm dust} = 1.087\left(\frac{A_\lambda}{A_V}\right)\left(\frac{A_V}{N_{\rm H}}\right)_{\odot} Z\,N_{\rm H}\,. \qquad (3)$$

The extinction spectrum of Mathis (1990) is adopted for (A_λ/A_V), and the extinction efficiency is assumed to be proportional to the relative heavy element abundance, and $(A_V/N_{\rm H})_\odot$ is the conversion factor from A_V to $N_{\rm H}$ for the local abundance listed in Table 2.

Finally, we obtain the absorption line flux with extinction, $I^{\rm abs}_{\rm line}$, as

$$\begin{aligned} I^{\rm abs}_{\rm line} &= I^{\rm abs}_{\rm line,0}\exp(-\tau_{\rm dust}) \\ &= S\Delta\nu(1-\exp(-\tau_{\rm line}))\exp(-\tau_{\rm dust})\,. \end{aligned} \qquad (4)$$

3. Results

The calculation was made for the five lines listed in Table 3. Parameters used here are from Turner et al. (1977). First, it is interesting to compare the optical thickness of the line absorption and the dust extinction. In case of $\Delta v = 100\,{\rm km\,s^{-1}}$ and the local heavy element abundance, the ratio of the line optical thickness to the dust optical thickness is 10^{-4} for vib-rotational lines in NIR, 10^{-3} for pure rotational lines in MIR, and 10^{-2} for pure rotational lines of HD in the FIR. It means that the absorption measurement is certainly difficult against the large extinction in the absorbing cloud. However, this ra-

Table 2. Parameters assumed for the present calculation.

Ortho : Para	3 : 1
HD/H_2	10^{-5}
Intrinsic Flux of Source	10 mJy
Line width	100 $\mathrm{km\,s^{-1}}$
Detection Limit (5σ) [a]	$5\times10^{-21}\ \mathrm{W\,m^{-2}}$
Detectable Optical Thickness	>0.01
Dust Extinction Model	Mathis (1990)

a: Expected detection limit of the *SPICA* mission (Ueno et al. 2000).

Table 3. Parameters of the Line Transitions.

Transition	Wavelength [μm]	A Coefficient [$\mathrm{s^{-1}}$]	$\mathcal{N}_{H_2}$ [$\mathrm{cm^{-2}}$] for $\tau_{\rm line}=0.01$	A_λ/A_V
H_2 $v=1-0$ $S(1)$	2.12	3.47×10^{-7}	4×10^{23}	0.11
H_2 $v=1-0$ $S(0)$	2.22	2.53×10^{-7}	8×10^{23}	0.11
H_2 $v=0-0$ $S(1)$	17	4.77×10^{-10}	7×10^{23}	0.020
H_2 $v=0-0$ $S(0)$	28	2.95×10^{-11}	3×10^{24}	0.011
HD $v=0-0$ $R(0)$	112	2.54×10^{-8}	2.5×10^{24}	0.0011

tio increases with the inverse of the heavy element abundance. Therefore, in the lower heavy element abundance case, we can expect reasonably higher ratios.

It is quite difficult to detect absorption lines whose optical thickness is less than 1 %. Therefore, as seen from Table 2, only those clouds whose column density is larger than 10^{24} $\mathrm{cm^{-2}}$ can be detected in absorption.

Figure 1a shows the absorption line flux expected for a cloud with the local heavy element abundance in front of a 10 mJy source. The absorption fluxes are far smaller than the 5σ expected sensitivity of the *SPICA* mission (Ueno et al. 2000). On the other hand, Figure 1b shows the result for the case in which the heavy element abundance is 1 % of that of the local one. All five lines populate parameter space above or near the limit.

Figure 2 shows the result of the same calculation, but for the H_2 $v=0-1$ $S(1)$ line for various values of the heavy element abundance. In case of $N_{H_2}>10^{24}$ $\mathrm{cm^{-2}}$ and $Z<0.01$, the absorption line can be detected.

4. Discussion

4.1. Possible Energy Source

In this subsection we discuss possible energy sources at high redshifts. In our calculations, we have assumed an intrinsic continuum flux density of 10 mJy at the line wavelength. What sort of flux density can we expect from high-z objects? To investigate this, we have plotted in Figure 3 the SED in the rest system of several high redshift objects for which observations are available. The sources and references for them are as follows: IRAS F10214 + 4724 ($z=2.286$; Rowan-Robinson et al. 1993; Barvainis et al. 1995), H1413 + 117 ($z=2.558$; Barvainis et al. 1995), SMM 02399 − 0136 ($z=2.8$; Ivison et al. 1998), SMM J14011 + 0252 ($z=2.55$; Ivison et al. 2000), APM 08279 + 5255 ($z=3.87$; Lewis et al. 1988), and BR 1202 − 0725 ($z=4.69$; Isaak et al. 1994). In this plot we have not corrected for the possible lens amplification for the first three objects and all observations have been transformed to a common redshift of 5 ($q_0=0.1$). The rest system SEDs and flux densities of F10214 + 4724 and H1413 + 117 are almost identical and encompass three of the lines – 17, 28, and 112 μm. The interpolated flux densities at the three frequencies are 8, 16, and 9 mJy respectively. For the rest of the sources, we extrapolate from the observed 450 μm flux density assuming the rest system SED to be the same as that of F10214 + 4724. From this exercise we find the range of flux densities to be 1.6–19 mJy at 17 μm, 3–37 mJy at 28 μm, and 2–21 mJy at 112 μm. On the other hand, if we use the SED of Arp 220, the expected flux densities are about 38 times larger at 17 μm, 11 times at 28 μm, and about the same at 112 μm. For distant highly luminous sources, Arp 220 SED may not be appropriate since Solomon et al. (1997) find that for a sample of ultraluminous IR galaxies out to a redshift of 0.3, the emission at 100 μm may be optically thick. Following their finding, if we use a 60 K blackbody spectrum as a template, the expected flux densities at 17 and 28 μm are a factor of 5 and 3 lower as compared with using Arp 220 SED.

Thus, if we have objects at $z=5$ at least as luminous as our template sources, it is possible to observe absorption in H_2 lines of 17, 28, and 112 μm respectively. The redshifted 112 μm line will be in the submm range and may not be observable by space missions of near future. However, the proposed large area and high sensitivity ground-based mm–submm interferometric arrays like ALMA should be able to observe it. Unfortunately, it is very difficult to observe the absorption of 2.2 μm lines since the expected flux density based on dust emission spectrum is a factor of 10 or more lower as compared with that at 17 μm. However, if a bright non-thermal flat spectrum source is present, absorption measurement at 2.2 μm may be possible.

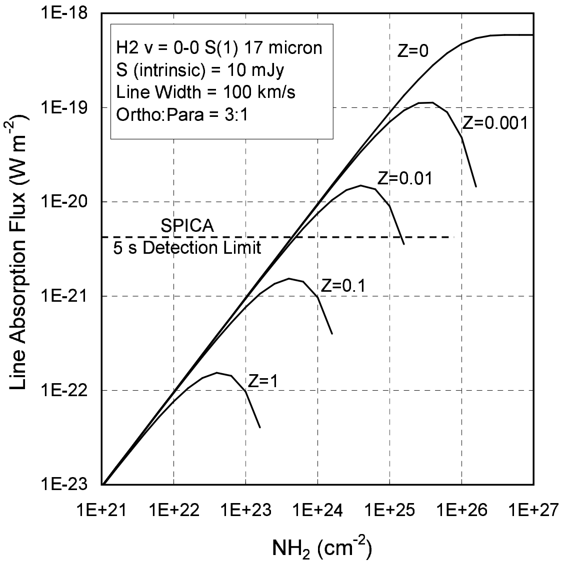

Fig. 2. Result of the same calculation as in Fig. 1, but for the H_2 $v = 0-0$ $S(1)$ line in various values of the heavy element abundance.

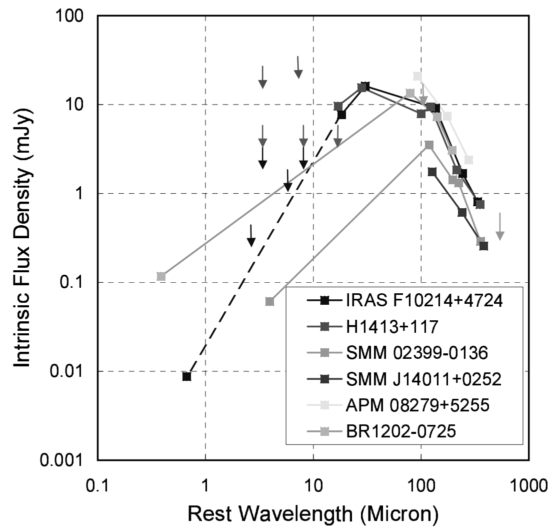

Fig. 3. The spectral energy distributions of six representative high-z objects. Downward arrows represent the upper limits.

4.2. What can we learn from the absorption lines of primordial clouds?

First we simply estimate the column density of a protogalactic hydrogen cloud. Here we assume that the size of the cloud R is a few kpc and that the gas mass M is $\sim 10^{11}$ $M_\odot$. Such a large reservoir of molecular gas has been discovered at high redshift (Papadopoulos et al. 2001). Such clouds have column density of

$$N_{\mathrm{H_2}} \simeq 4 \times 10^{23}\,[\mathrm{cm}^{-2}]\, f \left(\frac{R}{3\,[\mathrm{kpc}]}\right)^{-2} \left(\frac{M}{10^{11} M_\odot}\right). \quad (5)$$

where f is the mass fraction of the molecular clouds to the total gas mass, and M is the total gas mass of the protogalaxy. The final fate of such a large reservoir of gas may be the formation of a giant galaxy, whose typical core radius is a few kpc. If such a collapse really occurs in the formation epoch of galaxies, resulting column density is as large as the minimum column density (7×10^{23} cm^{-2}) needed for detecting H_2 line absorption.

In a realistic situation, a primordial cloud may evolve dynamically on a free-fall timescale. The free-fall timescale is much shorter than the timescale of cosmological structure evolution, e.g. the Hubble timescale. Therefore, observed properties are specific to the redshift at which the cloud absorption is measured. We will obtain redshift z, and velocity dispersion Δv. The present structure formation theory provides us the relation between the velocity dispersion and the corresponding dynamical mass of the cloud as a function of redshift, $M_{\mathrm{vir}}(z)$ (cf. Padmanabhan 1993). Thus, we can constrain the structure formation theory. The SPICA mission will provide us with the information on the massive objects ($\gtrsim 10^{11}$ M$_\odot$) at $z \lesssim 5$. We still have to wait for more sensitive facilities for the observational approach to the "Population III" objects, whose physical properties are theoretically predicted by recent extensive investigations, because they are located at higher redshift and their typical mass is small (e.g., Nishi & Susa 1999). When we estimate the detectability of such objects by other facilities, the algorithm constructed in this paper can be applied straightforwardly.

The above estimate (equation 5) is based on the mean column density of a galaxy. If we have a chance to detect the final phase of a collpsing gas in the line of sight of a quasar, we can constrain the physical state of such a collpase. In other words, we will be able to measure the column density $N_{\mathrm{H_2}}$, and excitation temperature T_{ex}, which are interesting quantities in the context of the evolution of an individual cloud. Recent theoretical work (e.g., Omukai & Nishi 1998; Omukai 2000) proposes the following scenario. The collapsing primordial gas must radiate its gravitational energy before the first generation objects are born from it. However, the gas consisting of only hydrogen and helium atoms cannot cool efficiently below a few $\times 10^3$ K because their constituents do not have radiative transitions corresponding a few $\times$ 10 K to a few $\times 10^3$ K. Therefore, a much more efficient cooling process must be working at this stage of the Universe. The most plausible cooling process is vib-rotational and pure rotational lines of molecular hydrogen. If the molecular hydrogen is effectively produced in the collapsing primordial gas at a few $\times 10^3$ K, the expected time scale of the gas contraction is considerably reduced. Galli & Palla (1998) indicated that so called relic electrons would work there as effective catalyst to produce primordial molecular clouds. If we have a high-precision measurements and follow-up observations of the absorption cloud, we might be able to

pursue the dynamical evolution of the cloud and to compare the theoretical predictions.

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